

# Miscellaneous Stars in the OGLE Catalog of Periodic Variable Stars in the Galactic Bulge

A r k a d i u s z   O l e c h

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## Abstract

The first catalog of chromospherically active and ellipsoidal variable stars in the OGLE database is presented. The periods, the observed magnitudes and colors, their values free of interstellar extinction, and Fourier coefficients of light modulation are given for 549 stars. New color-magnitude diagrams based on new color determinations are presented. The chromospherically active stars are all among the bulge red giants, while the ellipsoidal binary stars are near the disk main sequence turn-off point. A discovery of a small group of very red ( $2 < (V - I)_0 < 6$ ) and bright, chromospherically active bulge giants ( $I_0 \approx 13$  mag) is also reported.

## 1 Introduction

The Optical Gravitational Lensing Experiment (OGLE) is a long term observing project of the Warsaw University Observatory, the Princeton University Observatory and the Carnegie Institution of Washington, which begun in 1992. Its main goal is a search for dark matter in our Galaxy using the microlensing phenomena (Paczynski 1986, Udalski *et al* 1992). For this purpose the CCD photometry of a few millions stars in dense Baade's Window in Galactic bulge was performed. All the data was obtained with the 1-m Swope telescope at the Las Campanas Observatory in Chile, operated by Carnegie Institution of Washington, with a  $2048 \times 2048$  Ford/Loral CCD detector. In four seasons of photometric observations (1992–95) nineteen microlensing events have been detected (Udalski *et al* 1993, Udalski *et al* 1994a, Udalski *et al* 1994b, Paczynski & Udalski 1996).

Such a large amount of precise photometric data gives us opportunity to obtain many light curves of variable stars in the Galactic bulge. The first results of the OGLE search for periodic variables in Baade's Window were published by Udalski *et al* (1994c, 1995a, 1995b, 1996) as The Catalog of Periodic Variable Stars in the Galactic Bulge. The first three parts of the catalog presented results for the central part of Baade's Window (nine  $15' \times 15'$  fields centered at  $\alpha = 18^h03^m24^s$   $\delta = -30^\circ02'00''$ ), the fourth part contains data for three  $15' \times 15'$  fields on the eastern side of Baade's Window. The Catalog contained stars with  $\langle I \rangle$  in the range 14–18 mag. The upper limit  $I \approx 14$  mag is a result of saturation of stellar images on CCD frames, and the lower one is due to rapidly increasing photometric errors. Although the period search was limited to periods from 0.1 day to 100 days, there are a few  $\delta$  Scuti

stars with periods  $< 0.1^d$  which were identified with  $2 \times P$ , and a few Mira type variables with periods  $> 100^d$ .

The variable stars discovered in every field were grouped into three categories: pulsating stars (mostly RR Lyr and  $\delta$  Sct stars), eclipsing stars (mostly W UMa,  $\beta$  Lyr and Algol type) and miscellaneous variables (mostly late type, chromospherically active stars, some ellipsoidal variables and few Miras).

Equatorial coordinates (epoch 2000.0) of the BW fields, the number of the variable stars detected in each category are given in Table 1.

Table 1

The equatorial coordinates and numbers of detected stars in the OGLE Catalog.

BW Field	Equatorial Coordinates	Pulsating Stars	Eclipsing Stars	Miscellan. Stars
BWC	$18^h03^m24^s - 30^\circ02'00''$	31	116	66
BW1	$18^h02^m24^s - 29^\circ49'05''$	24	128	70
BW2	$18^h02^m24^s - 30^\circ15'05''$	13	100	56
BW3	$18^h04^m24^s - 30^\circ15'05''$	18	113	74
BW4	$18^h04^m24^s - 29^\circ49'05''$	16	124	64
BW5	$18^h02^m24^s - 30^\circ02'05''$	18	91	65
BW6	$18^h03^m24^s - 30^\circ15'05''$	16	83	54
BW7	$18^h04^m24^s - 30^\circ02'05''$	18	93	55
BW8	$18^h03^m24^s - 29^\circ49'05''$	12	85	54
BW9	$18^h00^m50^s - 29^\circ49'05''$	19	125	81
BW10	$18^h00^m50^s - 30^\circ02'05''$	23	130	76
BW11	$18^h00^m50^s - 30^\circ15'05''$	17	93	67
Tot.	—	225	1281	782

The main aim of this paper is to provide more information for the “miscellaneous” variable stars in the BWC–BW8 fields. In our work we omitted the stars unambiguously classified as Mira type variables, and we obtained 549 stars suspected of chromospheric activity or ellipsoidal variability. The additional 224 miscellaneous stars from fields BW9–BW11 are not analyzed as there is no extinction map for this part of the sky.

## 2 Light Curves.

The OGLE Catalog of Periodic Variable Stars in Galactic Bulge contains an atlas with phased light curves and  $30'' \times 30''$  finding charts. The photometric data presented in the Catalog is available to astronomical community in electronic form via INTERNET (ftp host: *sirius.astro.uw.edu.pl*, directory */ogle/var\_catalog*). The photometry of each star is based on four seasons of observations (from 1992 to 1995). It is clearly visible that many stars classified as miscellaneous change their light curves from season to season. The most prominent example of such behavior is provided by the variable BWC V34. The  $I$  and  $V$  photometry of this star is presented on Fig. 1. On the other hand, there are variables with low amplitude, almost sinusoidal light curves, which do not vary from season to season. The variable

BWC V39 is representative of this group. The  $I$  and  $V$  light curves of this star are shown on Fig. 2. It is not hard to notice that the first group contains chromospherically active stars with spotted surface and the second one contains ellipsoidal variables. Unfortunately, distinguishing between these groups is not always as obvious as in the examples shown in Figs. 1 and 2.

It is desirable to be able to classify various light curves according to some algorithm, rather than by visual inspection. With a hope to make it possible we decided to construct Fourier fit to the light curves in the form:

$$I = a_0 + a_1 \cdot \sin 2\pi x + a_2 \cdot \sin 4\pi x + b_1 \cdot \cos 2\pi x + b_2 \cdot \cos 4\pi x \quad (1)$$

The fitting was done for every light curve in every season. The coefficients  $a_0, a_1, a_2, b_1, b_2$  were calculated by the Least Squares Method. Variable  $x$  is defined as  $x \equiv \frac{t-t_0}{P}$  and  $t_0$  is the time of the first observation. Table 2 summarizes our results. The columns of this Table contain the following informations:

1. Star designation. The letters  $a, b, c, d$  correspond respectively to seasons 1992, 1993, 1994, 1995.
2. Period in days.
3. Value of  $a_0$ .
4. Value of  $a_1$ .
5. Value of  $b_1$ .
6. Value of  $a_2$ .
7. Value of  $b_2$ .

The full version of Table 2 is available in electronic form via INTERNET from URL <http://www.astro.uw.edu.pl/~olech/misc.html>.

Fig. 3 and Fig. 4 give  $I$  light curves for all seasons for the above-mentioned representatives of our groups. Solid line corresponds to the fit given by the equation (1). Additionally, the values of  $a_1$  and  $b_1$  for twenty randomly chosen stars are shown on Fig. 5.

### 3 New Color Determination.

The first edition of the Catalog published by Udalski *et al* (1994c, 1995a, 1995b, 1996) gave  $V - I$  colors of variable stars based on a very few  $V$ -band measurements made during the first three seasons. The accuracy of  $V$  magnitude was  $\sim 0.05$  mag. The  $V - I$  color was estimated only at maximum brightness. In the 1995 season many new  $V$ -band observations were made, and in many cases it became possible to obtain good  $V$  light curves. Therefore, we decided to make new color determinations. The first step of this procedure was to fit the Fourier function (1) to the phased  $I$  light curves for the fourth season. Next, for the phase corresponding to every  $V$  point we calculated the  $I$  magnitude with the fitted function. The final  $V - I$  color of the star was obtained as an average value of all such determinations.

The new color-magnitude diagram (CMD) presented in Fig. 6 is based on new color determinations. The open circles represent miscellaneous variable stars and dots stars with constant brightness. Only 20% of non variable stars are plotted for clarity.

Recently Woźniak & Stanek (1996) proposed a new method of investigating interstellar extinction, based on the two band ( $V$  and  $I$ ) photometry, which uses the red clump stars to construct the reddening curve. Stanek (1996) applied this method to CMDs obtained

by the OGLE collaboration and he constructed the extinction map of the central part of Baade’s Window (fields BWC–BW8). We used this reddening map to calculate values of  $I_0$  and  $(V - I)_0$  free from extinction. Our results are summarized in Table 3. This table gives the star designation, its period in days,  $I$ ,  $V - I$ ,  $I_0$ ,  $(V - I)_0$ , the mean amplitude of the brightness of the star and the variation of this amplitude. The values of  $I_0$  and  $(V - I)_0$  are used to plot true CMD presented on Fig. 7. In this Figure only 5% of the non variable stars were plotted.

It is worthwhile to note that the values of interstellar extinction given by Stanek (1996) are correct only for the Galactic bulge stars, and not in the disk stars. Therefore the main sequence on our CMDs might be bluer than it reality should be.

## 4 Distinguishing Between Chromospherically Active and Ellipsoidal Variable Stars.

We attempted to divide the miscellaneous stars into two groups; the first one containing chromospherically active stars, and the second one with ellipsoidal variables. We expected that chromospherically active stars, due to their changing light curves, should have a large scatter of their amplitudes. Therefore we plotted a correlation between the mean amplitude of the modulation of each star and Gaussian variation –  $\sigma$  of this amplitude from season to season. The result of this operation is shown in Fig. 8. Unfortunately, there is no clear distinction between the two groups, perhaps because many chromospherically active stars have small amplitudes.

Next, we tried another approach to separate the two types of variables. If a variable with a small amplitude and a sinusoidal light curve is an ellipsoidal variables then its true period should be twice longer than the one listed in Table 2 and 3. Therefore, the light curve of such a star should be better described by coefficients  $a_{0.5}$  and  $b_{0.5}$  (corresponding to the period  $2 \times P$ ) than  $a_1$  and  $b_1$ . This property could be visible in a graph showing the dependence of  $\sqrt{a_1^2 + b_1^2}$  on  $\sqrt{a_{0.5}^2 + b_{0.5}^2}$ . Such a graph is presented in Fig. 9. Unfortunately, no clear separation into two groups is apparent.

The next step was to plot the period of a star versus its brightness, as shown in Fig 10a. All limits of the Catalog are clearly visible. The upper limit near  $I = 14$  mag is a result of a saturation of stellar images on the CCD frames. The  $I = 18$  mag is a limiting magnitude of the present Catalog. The left and right boundaries result from the range of period search. A very interesting feature is the absence of stars in the upper-left part of the Figure. In order to check its physical nature we slightly modified our graph. We changed vertical axis from  $I$  to  $I_0$ , and the absence of stars in the upper-left part of Fig. 10b is just as clear as it was in Fig. 10a. This phenomenon is not due to the Catalog, but it has a physical cause: a variable of a given luminosity cannot have a period shorter than some limit. The solid line on Fig. 10b represents the minimal period of a rotating single star rotating at the so called “break-up”. The line was obtained in the following way: we adopted a linear relation between  $V_0$  and  $(V - I)_0$ , as calculated with the Least Squares Method:  $(V - I)_0 = 0.07574 \cdot V_0 + 0.03272$ . The dependence between  $(V - I)_0$  and the effective temperature  $T_{eff}$  of a star was taken from Bartelli *et al* (1994), with  $T_{eff} = 5000$  K corresponding to  $(V - I)_0 = 0.97$  mag and  $T_{eff} = 3500$  K to  $(V - I)_0 = 2.40$  mag. Assuming a typical stellar mass as  $1M_\odot$  and the distance of 8 kpc we obtained a relation which may be well approximated with:

$$I_0 = -3.58 \cdot \log P + 16.05 \quad (2)$$

where the period  $P$  is measured in days.

The line in Fig. 10b is a good envelope to the distribution of stars, and this demonstrates that the absence of stars in the upper-left part of the Figure is due to the physical limit. Only one star is placed considerably above the limiting line for a single rotating star. It might be a one star which is a result of mixing two stars of a binary system.

The color-magnitude diagram presented in Fig. 7 contains a few blue stars with  $(V - I)_0 < 1$ , which are placed mainly at the Galactic disk main sequence turn-off point. These stars are clearly separated from other miscellaneous variables, which are distributed above the bulge main sequence turn off point, on the red sub giant and the red giant branch. We decided to use a subjective judgement about the nature of these blue variables, and for every star with  $(V - I)_0 < 1$  we classified its light curve: those with most regular variations were expected to be ellipsoidal variables, those with the most irregular light curves were expected to be chromospherically active. Three groups were formed, and they are listed in Tables 4a, 4b, 4c.

Table 4 contains periods, magnitudes and colors of those blue stars which have light curves strongly resembling ellipsoidal variables. It is worthwhile to note that almost all stars so selected have very short periods and colors in the range  $0.3 < (V - I)_0 < 0.8$ . Table 5 contains blue stars which light curves could belong to ellipsoidal variables but its connection with chromospherically active stars cannot be excluded. It is clearly visible that periods of these stars are not restricted to such a small range as in Table 4, but in many cases the periods are still short. The colors of these stars are mostly in the range 0.8–0.9 mag. The last group is presented in Table 6 and contains blue stars which light curve definitely excluded connection with the ellipsoidal variability. The range of periods of stars in this group is very large, and the colors are very close to 1.0 mag.

We believe that objects listed in Table 4 and the majority of these listed in Table 5 are ellipsoidal variable stars. These blue stars are shown in the color-period diagram in Fig. 11 with open circles, and they form a narrow branch of a few points with blue color and short period.

The full list of OGLE stars with V and I data contains 528 138 objects. It is not a precise estimate because of photometric errors (see for comparison Szymański *et al* 1996). We estimate that in area the below red clump i.e. for  $14.5 < I_0 < 16$  and  $(V - I)_0 > 1$ , there are 24 744 constant stars. In the same region there are 273 miscellaneous variable stars. It means that about 1% of all stars in that part of CMD is chromospherically active with amplitude of modulation large enough to be detected in the OGLE search. Of course there are variables classified as miscellaneous also outside the above-mentioned area, but their highest concentration is observed inside this area.

Two normalized histograms of color distribution in 0.1 mag bins are presented in Fig. 12 for stars with  $15.0 < I_0 < 16.0$ . The solid and dotted lines correspond to constant and to variable stars respectively. The distribution of the colors in both cases seems to be similar, but the dotted line is slightly redder than the solid one.

## 5 Red stars.

Among the few hundred miscellaneous variables we found eight exceptionally red stars which are clearly visible in the CMD presented in Fig. 13. Our first impression was that  $V$ -band brightness of these star was measured incorrectly. Therefore, we investigated  $V$ -band light curves of these stars and we found that they are phased with the same periods as  $I$ -band light curves. A large number of  $V$  data points excludes a possibility of a mistake, as demonstrated in Fig. 14 and 15, where  $I$  and  $V$  light curves of these stars are presented.

The following stars belong to this group are BW1 V1, BW3 V1, BW3 V2, BW5 V5, BW6 V3, BW7 V1, BW7 V5, BW8 V2 and also variable V1 in the field BW9. These red stars are distinguished not only by the large values of  $(V - I)_0$  but also by their high brightness and long periods. They are often the brightest variable stars in their fields. It would be interesting to search for such red variables among the stars brighter than  $I \approx 14$ , which is the upper limiting magnitude of the Catalog.

Previous surveys of Baade's Window region (Frogel & Whitford 1987, Blanco *et al* 1984, Lloyd Evans 1976) also revealed examples of such red and bright objects. The majority of the reddest stars in those surveys was variable, and because of their large amplitudes and long periods they were classified as Mira type variables. Additionally a large part of their variables was semiregular. The red stars presented in this paper are certainly not Miras, but they may be semiregular variables. Their periods are shorter than 100 days, their light curves are unstable and change from season to season. It suggests that these objects belong to the group of chromospherically active variables, but we cannot exclude the possibility that they are semiregular variables.

Similar red and bright objects were also found in a few open clusters. For instance, Garnavich *et al* (1994) reported observations of the red giant branch in old and metal rich open cluster NGC 6791. They found at least 12 such stars. These objects are placed at the end of evolutionary sequences of stars with masses near  $1.1M_{\odot}$ . In the same cluster Kałuzny & Ruciński (1993) discovered 17 variable stars. One of them was very red  $B - V = 1.595$  evolved giant and was located above the horizontal branch red clump. They suggested that variability of this star was caused by pulsations and classified it as RV Tau-type star.

## 6 Conclusion and Summary

We have presented the first catalog of stars classified as miscellaneous in the OGLE search for variable stars in the Galactic bulge. Our catalog contains 549 objects. The periods, the magnitudes and colors as observed and free of interstellar extinction, the coefficients of Fourier fit and amplitudes of the light modulation are given for each star. 517 object are suspected for chromospherical activity. Some of these stars are likely to be single rotating spotted stars of the FK Com type. Other objects from this group could be binary systems with spotted component, like RS CVn binaries. 32 stars with colors  $(V - I)_0 < 1$ , short periods and sinusoidal, small amplitude light curves are classified as ellipsoidal variables i.e. binary systems with ellipsoidal components not showing eclipses.

A group of 8 stars from our list is distinguished by the very large values of  $(V - I)_0$  color (in range 2.5–6 mag), and high and similar  $I$ -band brightness, near the bright limit of the OGLE catalog. These are likely to be chromospherically active red giants. It is interesting that there are no constant stars at the part of CMD where our reddest variables are located. Similar property was presented by Frogel & Whitford (1987) where variables

were also the reddest M giants found. It might suggest that the spots on the stellar star cause a considerable reddening of the star.

The chromospherically active stars in the are almost uniformly spread along red subgiants, giant and super giant branches, where they constitute about 1% of all stars in the OGLE database. There is no clear concentration of these variables in the red clump region of the CMD, which suggest that spotted stars evolve for the first time along the red giants branch.

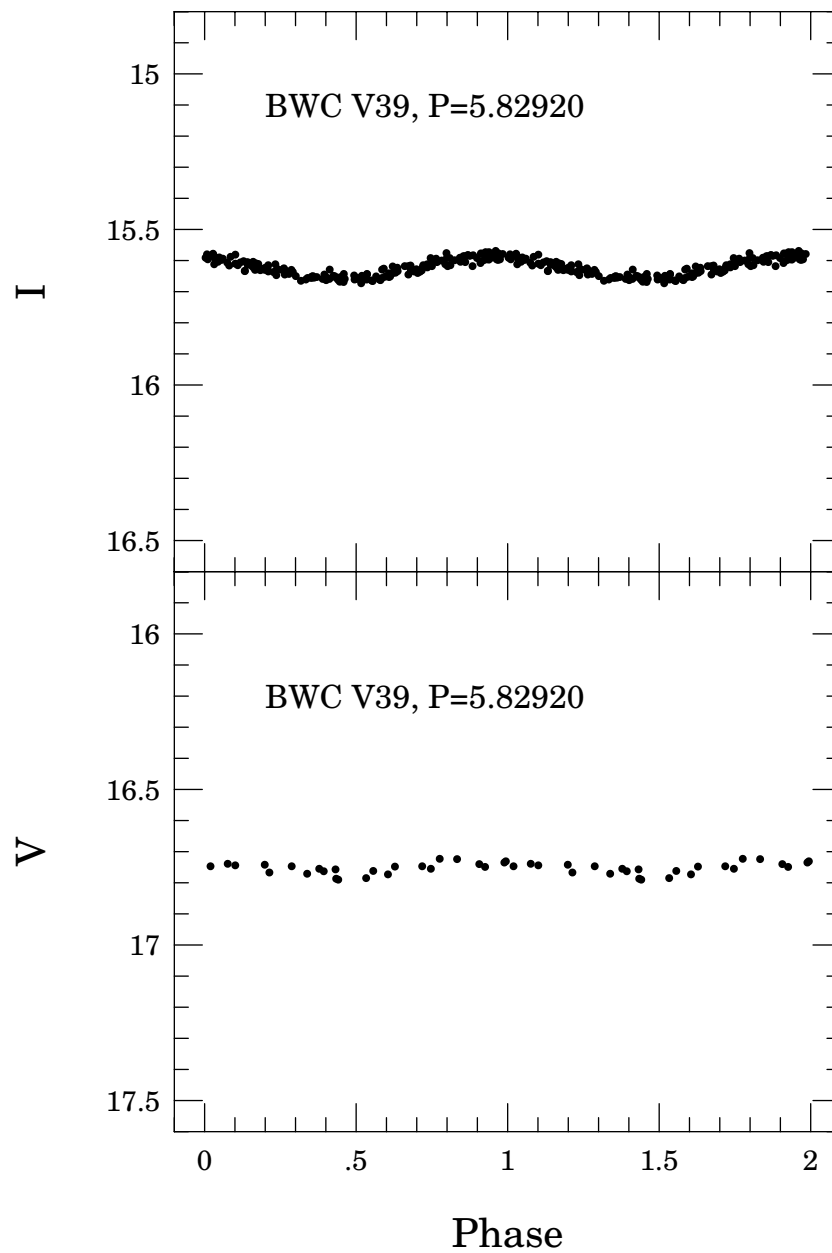
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## REFERENCES

- Bartelli, G., Bressan, A., Chiosi, C., Fagotto, F., and Nasi, E. 1994 *Astron. Astrophys. Suppl. Ser.* 106 275
- Blanco, V.M., McCarthy, M.F., and Blanco, B.M. 1984 *Astron. J.* 89 636
- Frogel, J.A., and Whitford, A.E. 1987 *ApJ* 320 199
- Garnavich, P.M., VandenBerg, D.A., Zurek, D.R., and Hesser, J.E. 1994 *Astron. J.* 107 1097
- Kałużny, J., and Ruciński, W. 1993 *MNRAS* 265 34
- Lloyd Evans, T. 1976 *MNRAS* 174 169
- Paczynski, B. 1986 *ApJ* 304 1
- Paczynski, B., and Udalski, A. 1996 *The proceedings of 12th IAP Colloquium: Variable Stars and the Astrophysical Returns of Microlensing Surveys*
- Stanek, K.Z. 1996 *ApJ Letters* 460 37
- Szymański, M., Udalski, A., Kubiak, M., Kałużny, J., Mateo, M., and Krzemiński, W. 1996 *Acta Astron.* 46 1
- Udalski, A., Szymański, M., Kałużny, J., Kubiak, M., and Mateo, M. 1992 *Acta Astron.* 42 253
- Udalski, A., Szymański, M., Kałużny, J., Kubiak, M., Krzemiński, W., Mateo, M., Preston, G.W., and Paczyński, B. 1993 *Acta Astron.* 43 289
- Udalski, A., Szymański, M., Stanek, K.Z., Kałużny, J., Kubiak, M., Mateo, M., Krzemiński, W., Paczyński, B., and Venkat, R. 1994a *Acta Astron.* 44 165
- Udalski, A., Szymański, M., Kałużny, J., Kubiak, M., Mateo, M., Krzemiński, W., and Paczyński, B. 1994b *Acta Astron.* 44 227
- Udalski, A., Kubiak, M., Szymański, M., Kałużny, J., Mateo, M., and Krzemiński, W. 1994c *Acta Astron.* 44 317
- Udalski, A., Szymański, M., Kałużny, J., Kubiak, M., Mateo, M., and Krzemiński, W. 1995a *Acta Astron.* 45 1
- Udalski, A., Olech, A., Szymański, M., Kałużny, J., Kubiak, M., Mateo, M., and Krzemiński, W. 1995b *Acta Astron.* 45 433
- Udalski, A., Olech, A., Szymański, M., Kałużny, J., Kubiak, M., Mateo, M., Krzemiński, W., and Stanek K.Z. 1996 *Acta Astron.* 46 51



Woźniak, P., and Stanek, K.Z. 1996 *ApJ* 464 233



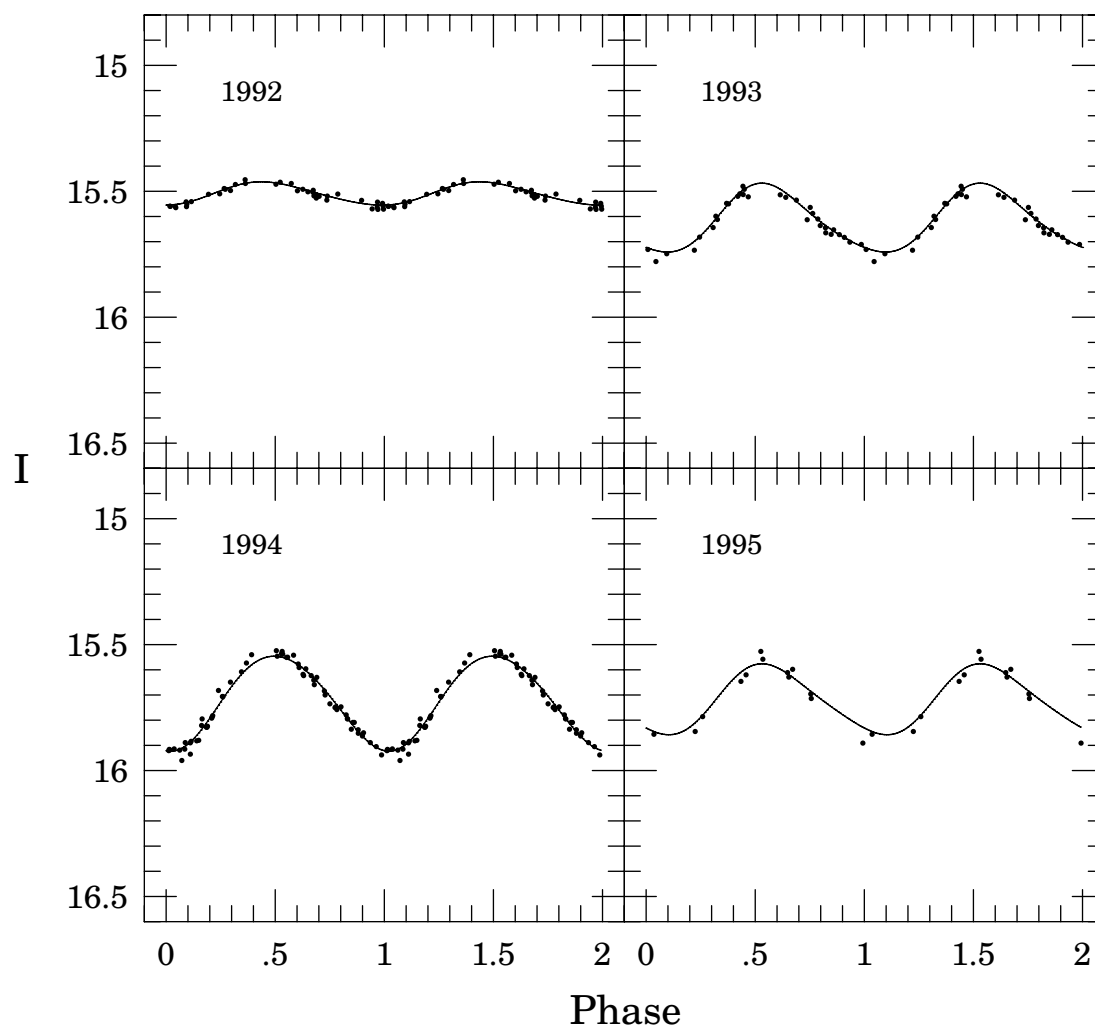


Table 4a

Star Designation	Period [days]	$I$ [mag]	$V - I$ [mag]	$I_0$ [mag]	$(V - I)_0$ [mag]
BWC V39	5.82920	15.623	1.159	14.596	0.482
BWC V45	6.67334	15.653	1.163	14.733	0.547
BWC V69	3.48129	16.085	1.189	15.020	0.497
BWC V72	5.31773	16.089	1.412	15.052	0.731
BW1 V58	3.25106	16.094	1.335	15.183	0.711
BW3 V5	19.06577	14.399	1.684	12.872	0.654
BW3 V34	4.32736	15.796	1.229	14.771	0.554
BW3 V49	1.57766	16.027	1.377	15.024	0.701
BW3 V60	4.98511	16.243	1.314	15.219	0.639
BW3 V102	1.44218	16.841	1.347	15.464	0.462
BW4 V77	2.11847	16.472	1.011	15.563	0.391
BW5 V58	3.43618	16.128	1.481	15.150	0.834
BW5 V65	11.33925	16.240	1.543	15.059	0.730
BW6 V11	8.44017	15.219	1.433	14.254	0.809
BW6 V74	5.33264	16.600	1.599	15.514	0.884
BW7 V58	5.06138	16.302	1.618	15.297	0.960
BW8 V4	13.67317	14.268	1.600	13.373	0.987
BW8 V17	6.51395	15.250	1.442	14.322	0.791
BW8 V52	3.19486	16.186	1.340	15.138	0.599
BW8 V83	2.61259	16.933	1.611	15.912	0.883

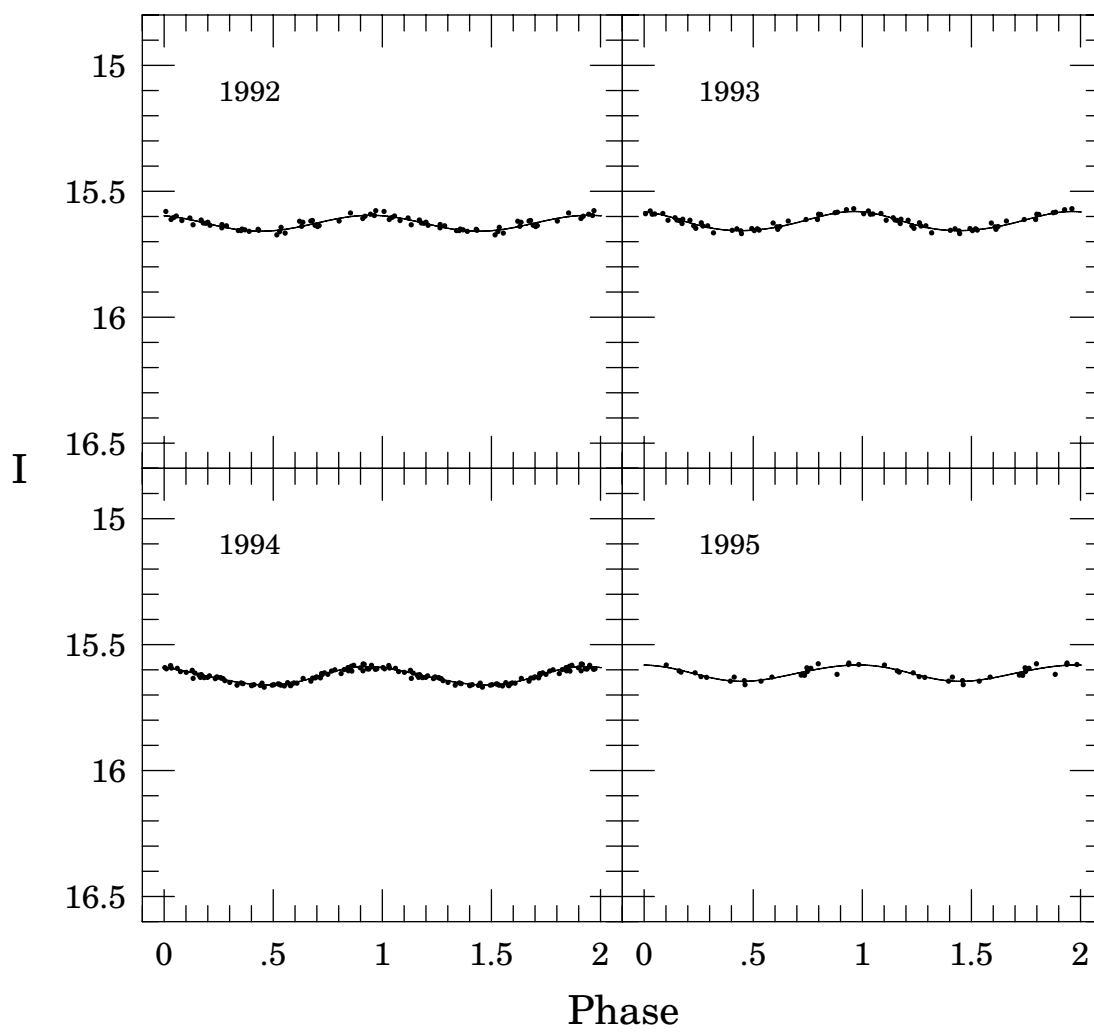


Table 4b

Star Designation	Period [days]	$I$ [mag]	$V - I$ [mag]	$I_0$ [mag]	$(V - I)_0$ [mag]
BWC V74	45.81902	16.177	1.492	15.295	0.896
BWC V119	4.09207	16.929	1.464	16.114	0.919
BW1 V27	9.21642	15.545	1.522	14.661	0.911
BW1 V45	2.59006	15.882	1.534	14.946	0.898
BW1 V72	7.52251	16.269	1.673	15.217	0.972
BW2 V115	6.25551	17.292	1.643	16.134	0.886
BW3 V72	7.11300	16.446	1.737	15.312	0.990
BW3 V118	1.80611	17.058	1.613	16.009	0.931
BW3 V145	20.11758	17.429	1.738	16.272	0.988
BW3 V168	17.65215	17.645	1.725	16.504	0.942
BW4 V18	52.37688	15.431	1.110	14.444	0.418
BW4 V59	42.31632	16.218	1.709	15.196	0.999
BW4 V128	2.56227	17.065	1.463	16.161	0.836
BW4 V139	5.69908	17.265	1.748	16.149	0.951
BW5 V142	2.72042	17.639	1.604	16.589	0.884

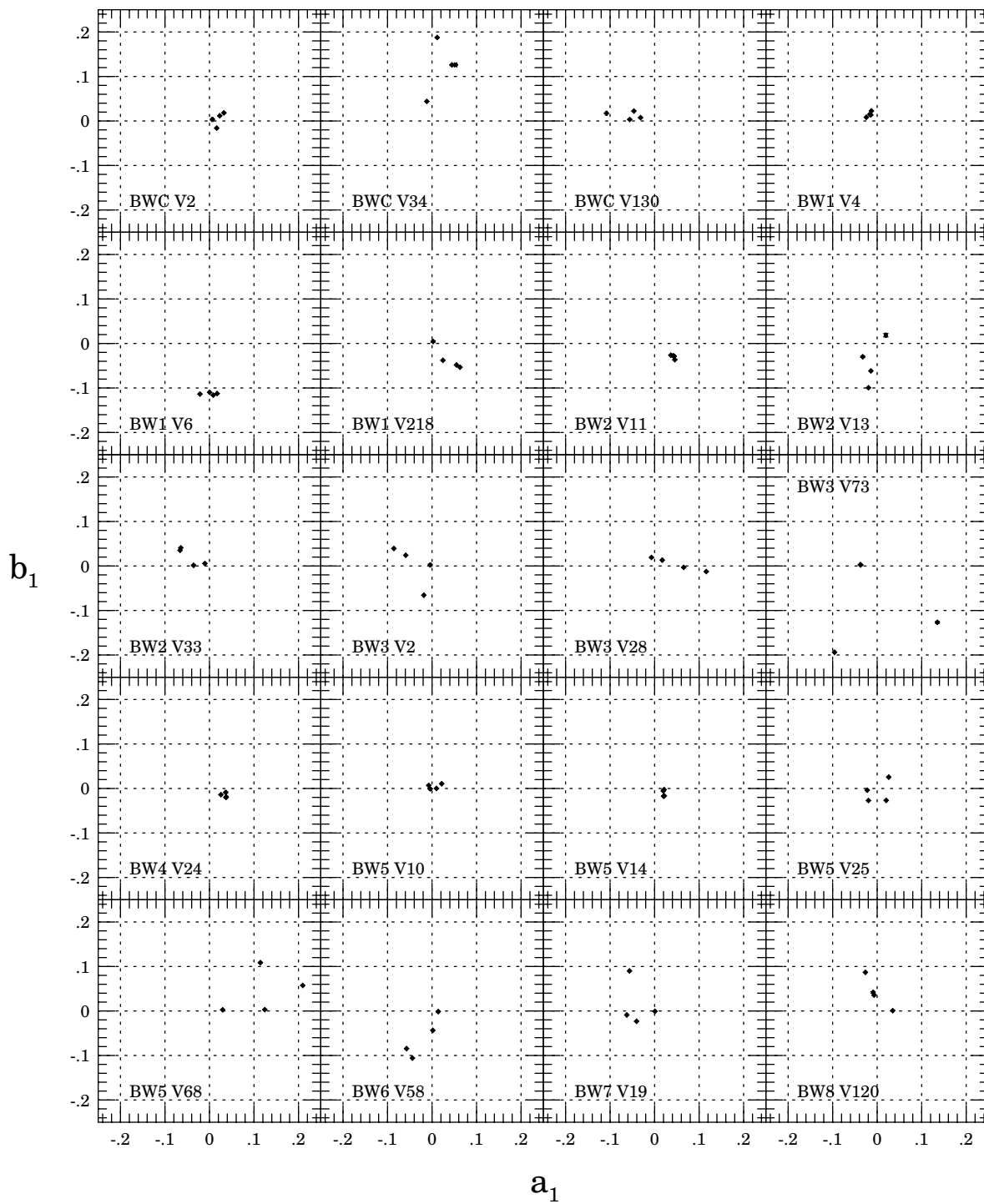
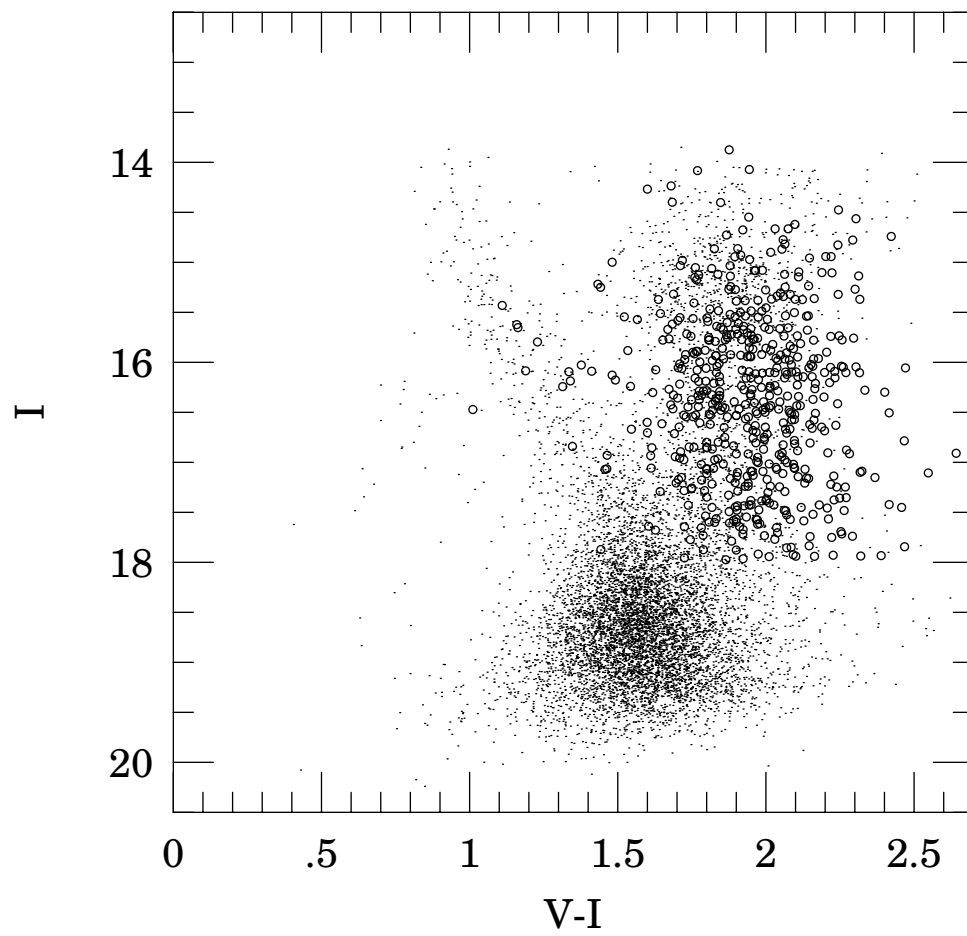
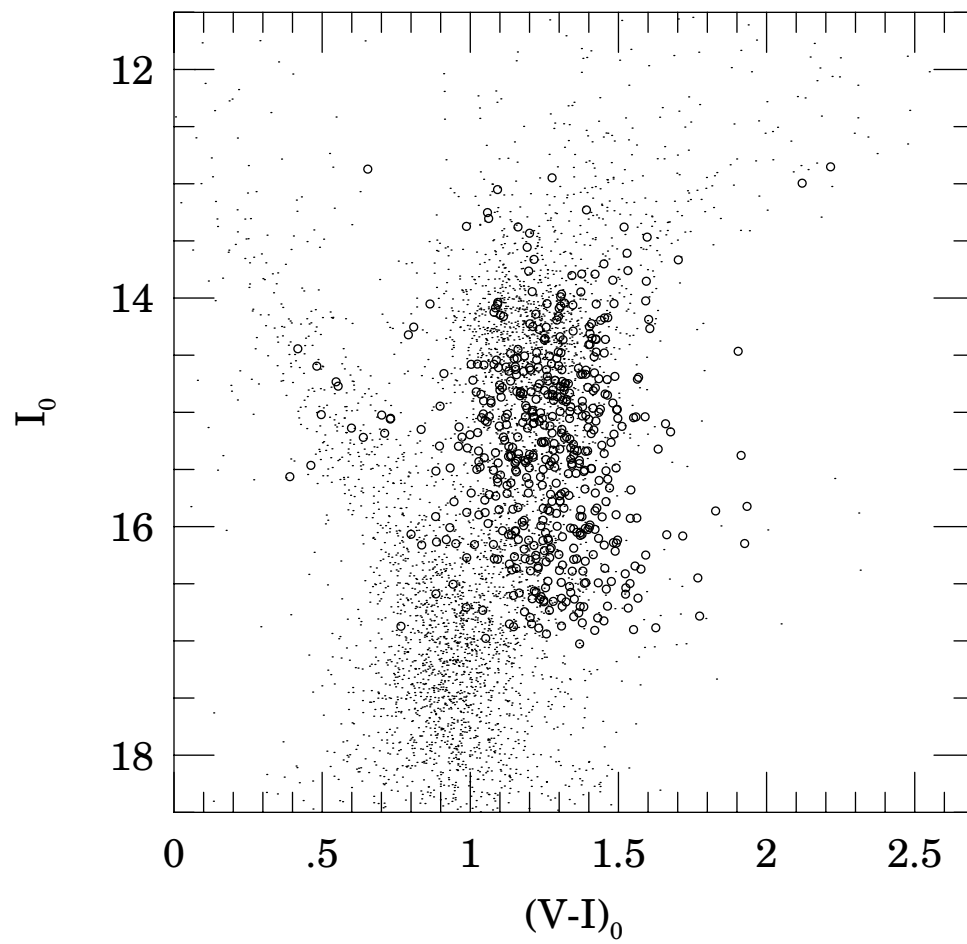


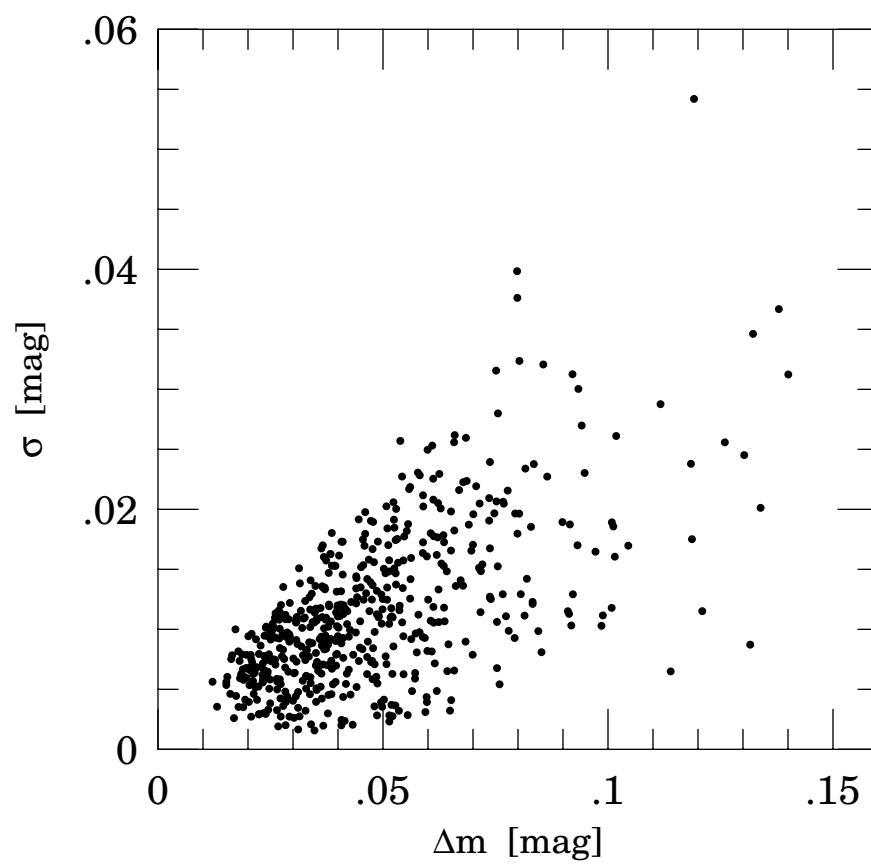
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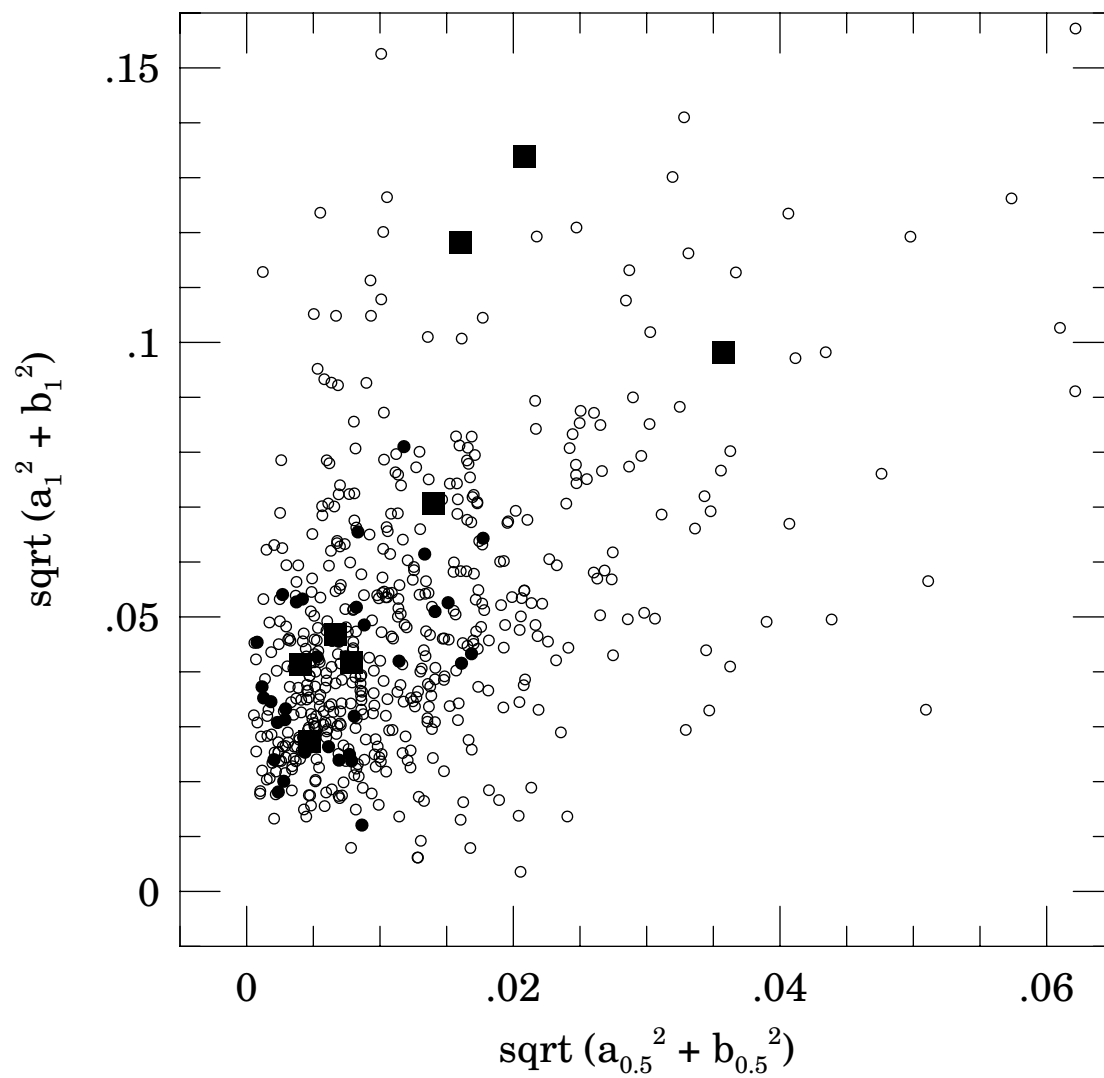
Star Designation	Period [days]	$I$ [mag]	$V - I$ [mag]	$I_0$ [mag]	$(V - I)_0$ [mag]
BW1 V114	28.26313	16.854	1.615	15.876	0.988
BW1 V196	12.60082	17.678	1.627	16.708	0.986
BW2 V66	3.83093	16.614	1.649	15.487	0.932
BW4 V202	64.80522	17.872	1.443	16.872	0.766
BW5 V63	28.22404	16.328	1.783	15.128	0.962
BW7 V10	16.12127	14.999	1.481	14.052	0.864
BW7 V99	57.53259	17.071	1.457	16.067	0.800

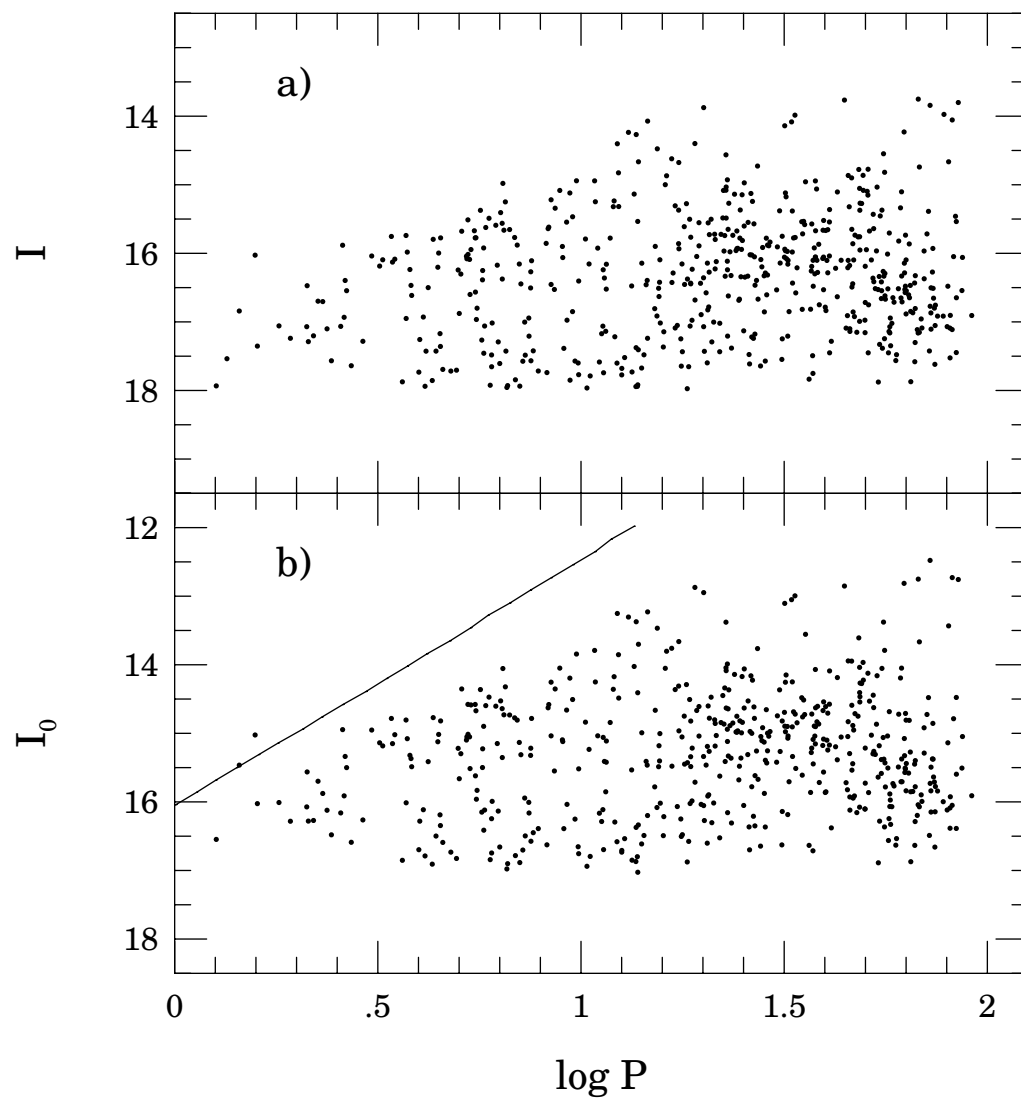


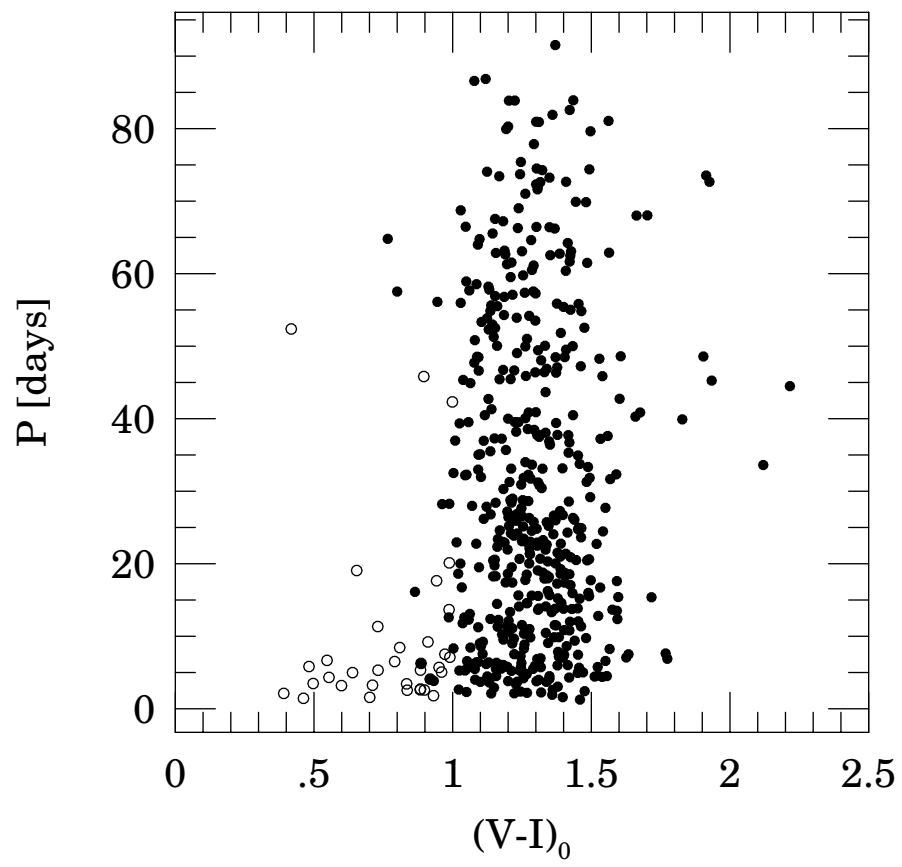












Stars with  $15 < I_0 < 16$

